

INTEGRATED MANAGEMENT OF RELIABILITY AND TECHNO-ECONOMIC EFFICIENCY OF VEHICLES BASED ON ENGINE AIR FILTER REPLACEMENT LOGISTICS

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Abstract. The paper addresses the issue of integrated management of the reliability and economic efficiency of vehicles based on the logistics of the engine air filter replacement. The study is aimed at assessing the impact of the engine air filter replacement intervals on the vehicle operational performance and maintenance costs under real-world operating conditions. The objects of the study are passenger vehicles of the Renault and Mazda brands, which are widely represented in transport and logistics systems. The methodology for studying air filters included the following stages: development of a test plan; conduct of operational tests; collection of empirical mileage data; assessment of the technical condition of the filters; statistical processing of the data; and determination of reliability indicators. The scheduled air filter replacement intervals declared by vehicle manufacturers and the actual operating conditions of vehicles in urban traffic and on dust-intensive road surfaces were analyzed. It was established that deviations from the optimal air filter replacement periodicity led to a reduction in the engine reliability indicators, an increase in fuel consumption, and higher operating costs. For this purpose, air filters from 25 vehicles of the same model for each brand were collected and analyzed. Based on experimental studies of the engine air filter replacement intervals for vehicles with different operating durations, the limiting permissible values of the technical condition were determined, which can be used as a criterion for making maintenance management decisions. A logistics-based approach to organizing the replacement and stocking of air filters is proposed, which enables improved operational reliability of vehicles and ensures the economic efficiency of their use within transport management systems. The results of the study can be used to develop effective maintenance programs and cost management strategies in transport and logistics systems.

Keywords: vehicle reliability, engine air filter, replacement interval, maintenance management, spare parts logistics.

Introduction

The durability and maintainability of internal combustion engines largely depend on the quality of the air–fuel mixture supply and the cleanliness of the intake air. Atmospheric air contains mechanical impurities – dust, sand, road surface wear products, and mineral particles – which, when entering the combustion chamber, cause abrasive wear of the cylinder–piston group components and reduce the engine service life. Studies indicate that the primary cause of such wear is dust particles composed mainly of hard mineral compounds (SiO_2 , Al_2O_3) with hardness exceeding that of the most structural engine materials [1].

Air intake systems protect the engine from abrasive particles, the air filter being their principal component. Its main function is to ensure a high degree of air cleanliness while maintaining minimal flow resistance. Modern multilayer filter elements made of cellulose or synthetic fibers achieve efficiencies exceeding 99.9% for particles larger than 2–5 μm ; however, particles greater than 1 μm remain the most hazardous for the engine, as they cause intensive abrasive wear [2].

During operation, dust particles accumulate in the filter material, altering the hydrodynamic characteristics of the airflow. This increases the aerodynamic resistance of the intake system, reducing cylinder filling, combustion efficiency, and engine fuel economy. Additionally, filter contamination affects the performance of electronic control systems that respond to changes in the airflow and air pressure.

The problem of improving the efficiency of air purification systems in internal combustion engines has been widely addressed in contemporary research [3; 4]. A considerable number of studies focus on the penetration of dust particles into the engine and the mechanisms of abrasive wear of its components. Research on the impact of dust on the engine operational reliability shows that even small amounts of abrasive particles in the intake air can significantly accelerate the wear of the cylinder–piston group components, plain bearings, engine blocks [3], and cylinder heads [4], thereby reducing the engine life.

Studies analyzing the characteristics of filter materials have made a significant contribution to the development of air filtration research. Experimental results demonstrate that filtration efficiency strongly depends on the structure of the fibrous material, pore size, filter layer thickness, and airflow velocity. The use of composite multilayer materials with nanofiber layers substantially increases the capture efficiency of fine particles and enhances the dust-holding capacity of the filter element [2].

A separate line of research is devoted to evaluating the operational condition of air filters and determining justified replacement intervals. Experimental data indicate that during operation, filtration efficiency exhibits a dual effect: dust accumulation in the material pores improves the retention of fine particles, while simultaneously causing a significant increase in the aerodynamic resistance in the engine intake system [5].

Most studies focus on laboratory testing of filter material properties or bench experiments, whereas the analysis of actual operational data is conducted much less frequently, which limits the possibilities for justifying rational maintenance intervals under real-world vehicle operating conditions. Operational studies provide objective information on evolution of the filter technical condition and the statistical characteristics of the service life. The performance of an air filter is determined not only by its initial properties but also by the dynamics of their change during operation. The main parameters include filtration efficiency, dust-holding capacity, and aerodynamic resistance of the airflow.

The scientific novelty of the study lies in combining operational observations with statistical reliability assessment methods to determine patterns of air filter service life degradation and to justify adaptive replacement intervals, taking into account real-world operating conditions.

The aim of this study is to identify the patterns governing the service life variation of engine air filters in mobile power units based on the analysis of operational data and statistical evaluation of their reliability, in order to substantiate rational replacement intervals for filter elements.

Materials and methods

The study of the operational reliability of air filters in internal combustion engines was carried out based on an integrated approach combining field observations, statistical data processing, and visual-analytical assessment of the technical condition of filter elements.

The objects of the study were engine air filters of passenger cars from two brands: vehicles equipped with gasoline engines of the SKYACTIV-G 2.0 type (Mazda) fitted with PE07-13-3A0A filters, and Renault vehicles equipped with air filters of the type 165467674R.

Vehicle operation was conducted under real conditions, including urban and mixed driving cycles, characterized by variable air dust concentration. Operating conditions were characterized by variable levels of airborne dust concentration, specifically elevated levels in heavy traffic zones and on road sections with dust-prone surfaces, which corresponds to typical vehicle operating environments. To ensure the representativeness of the results, a sample of filter elements was formed, consisting of filters operated until reaching their limit state or until replacement based on actual signs of engine performance deterioration. The sample included filter elements operated under standard conditions with no structural integrity breaches of the intake system, in the absence of emergency engine operating modes, and with full recording of mileage until replacement or reaching the limit state.

The research methodology was based on reliability testing under real operating conditions. The applied approach involved forming a sample of observation objects and recording the moments when the filtration system reached its limit state. According to the adopted testing scheme, the study included [6]: determination of the number of tested objects (N); recording the service life until replacement or failure of the filter (T); analysis of the filter condition after removal; and termination of observations upon reaching the limit state of the element.

This approach is consistent with methods used in durability and maintainability testing of technical systems and enables obtaining reliable data on the service life of air purification system components.

The technical condition of the air filters was assessed by comparing new and used filter elements (Fig. 1). Visual analysis made it possible to identify characteristic indicators of reaching the limit state, which were used as an additional criterion in determining the optimal replacement moment.

To evaluate the service life of air filters, methods of mathematical statistics and reliability theory were applied. Based on vehicle mileage data up to the time of filter replacement, statistical samples were formed for each brand. Using these data, the following were constructed: histograms of filter replacement intervals; frequency polygons; and empirical distribution functions.

The graphical dependencies, presented as diagrams for Mazda and Renault vehicles, reflect the variation in mileage to filter replacement and allow assessing the distribution pattern of the studied variable.

For the quantitative assessment of statistical characteristics, the following parameters were determined: mean time (mileage) to replacement, standard deviation, and coefficient of variation. The hypothesis regarding the type of the distribution law was tested using goodness-of-fit criteria (in particular, the Kolmogorov test). The choice of the normal distribution is justified by the fact that the studied parameter is formed under the cumulative influence of independent random operational factors, which aligns with the premises of the Central Limit Theorem. This made it possible to assess the applicability of theoretical distribution models for approximating empirical data. In addition, a comparative evaluation of statistical characteristics for the two vehicle brands was performed, enabling the identification of the influence of filter design features and operating conditions on their service life.

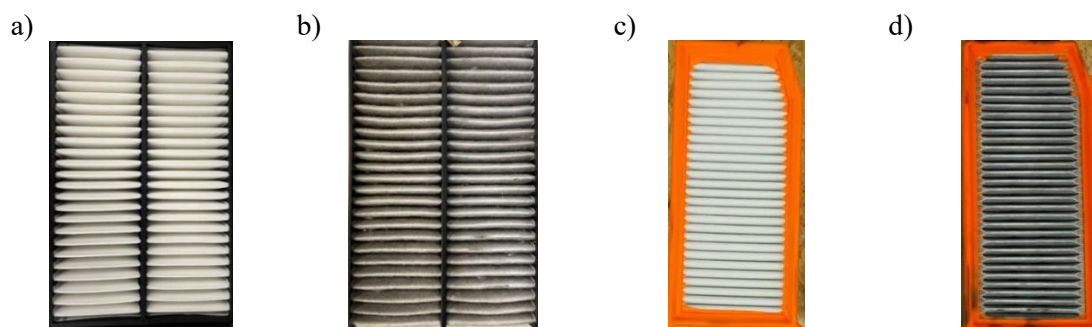


Fig. 1. PE07-13-3A0A air filters for SKYACTIV-G 2.0 engines in Mazda vehicles: **a** – new filter; **b** – filter inspected and replaced after 16.636 thousand km

Fig. 2. 165467674R air filters for Renault vehicle engines: **c** – new filter; **d** – filter inspected and replaced after 13.246 thousand km

The research methodology included these stages: selecting air filter samples from two vehicle brands, performing field observations until replacement, evaluating the removed filters visually and parametrically, preparing statistical datasets and graphs, determining service life statistics, and analyzing patterns in replacement intervals.

Results and discussion

Experimental studies were conducted on engine air filters of Mazda vehicles operated under real conditions of urban and mixed driving cycles. The sample included 25 filter elements of type PE07-13-3A0A installed on SKYACTIV-G 2.0 L engines.

During vehicle operation, the technical condition of the filters was monitored, including visual inspection, assessment of the contamination level of the filter material, and analysis of operational indicators reflecting the engine performance deterioration. Such indicators included reduced engine power, increased fuel consumption, and unstable idling.

For PE07-13-3A0A filters used in Mazda vehicles, characteristic stages of condition change depending on the service life were identified: initial state (new filter) – clean filter material with no deformation; intermediate state (≈ 5.300 thousand km) – partial dust accumulation and localized contamination; limit state ($\approx 17,000$ thousand km) – significant contamination, compaction of the filter layer, and reduced permeability.

Based on the obtained data, a statistical series of replacement intervals for PE07-13-3A0A air filters in SKYACTIV-G 2.0 L engines was formed (Fig. 3).

Processing of operational observation results showed that the mean mileage for filter replacement is 10.574 thousand km, while the standard deviation is 3.216 thousand km, indicating significant

variability in the filter service life under different operating conditions. The calculated coefficient of variation is 0.44, exceeding values typical for many technical systems. This result can be explained by the diversity of vehicle operating conditions, including both urban routes with intensive traffic and road sections with increased dust levels.

Based on the experimental data for Mazda engine filters, an empirical cumulative distribution function of the studied parameter was constructed (Fig. 4). Its approximation was performed using a normal distribution law. The obtained values of the mean and standard deviation indicate a higher variability of the studied parameter compared to similar data for other vehicle brands, which may be attributed to specific operating conditions or design features of the filter elements.

For Renault filters, a detailed qualitative and quantitative assessment was carried out, which revealed a reduction in the effective filtration area from 0.45-0.55 m² to 0.25-0.35 m²; a decrease in filtration efficiency from 97-98% to 70-80%; and deformation and clogging of the folds of the filter material. These changes are accompanied by deterioration in the engine performance, manifested in reduced power output and increased fuel consumption.

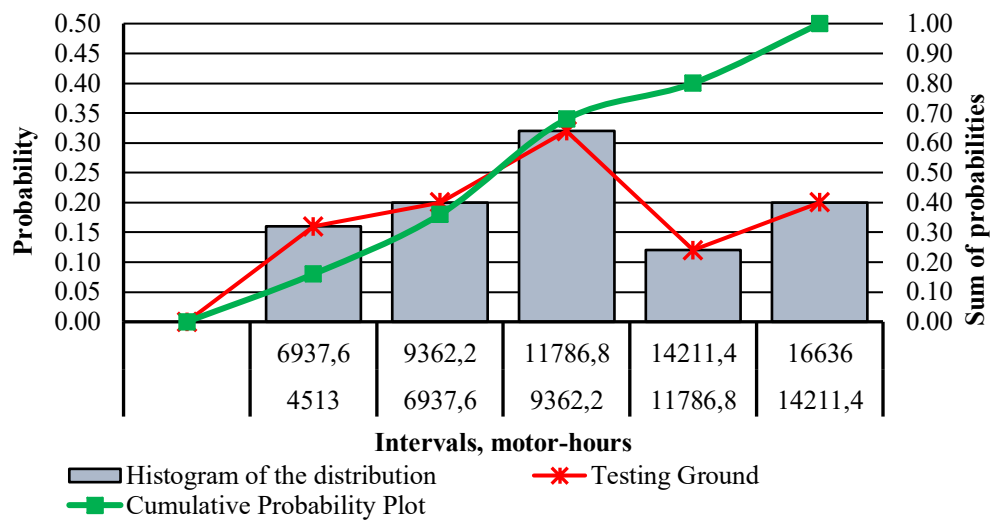


Fig. 3. Results of statistical analysis of replacement intervals for PE07-13-3A0A air filters in Mazda vehicle engines

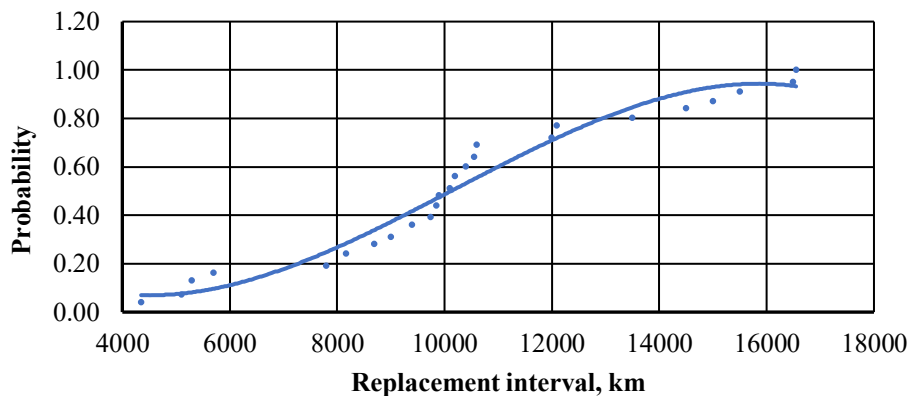


Fig. 4. Approximation of replacement interval distribution for PE07-13-3A0A air filters in Mazda vehicle engines

To evaluate the patterns of filter service life variation, a histogram and a frequency polygon of mileage to replacement were constructed (Fig. 5). Processing of the operational test results showed that the mean mileage to filter replacement is 9.561 thousand km, the standard deviation is 2.4 thousand km, and the coefficient of variation is 0.41. Analysis of the obtained results indicated that the empirical distribution approximately follows a normal law. The hypothesis of conformity to the theoretical distribution was tested using the Kolmogorov criterion.

To generalize the statistical data, an empirical cumulative distribution function of the studied parameter was constructed. Its approximation was performed based on the normal distribution law. The obtained results demonstrate satisfactory agreement between the experimental data and the theoretical model, which allows its application for predicting probabilistic characteristics of the service life of filter elements (Fig. 6).

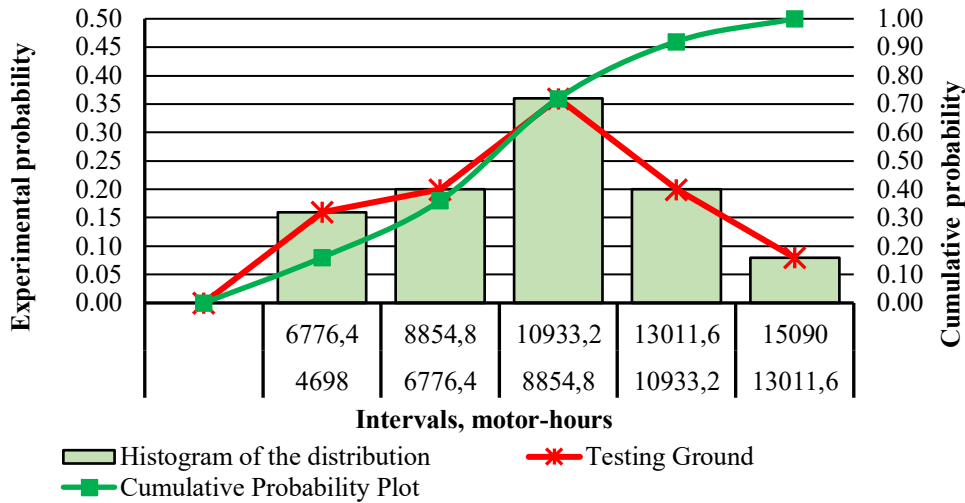


Fig. 5. Results of statistical analysis of replacement intervals for 165467674R air filters in Renault vehicle engines

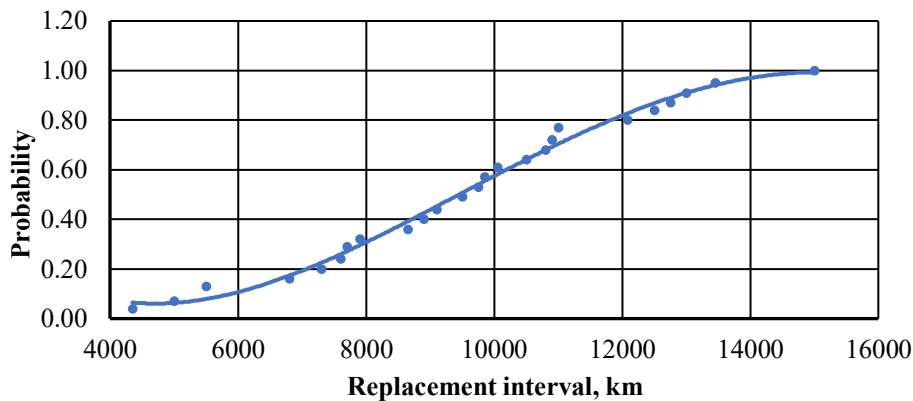


Fig. 6. Approximation of replacement interval distribution for 165467674R air filters in Renault vehicle engines

The obtained research results confirm that the replacement interval of engine air filters is a stochastic variable determined by a combination of operational, design, and environmental factors. The identified patterns have important practical implications for the development of maintenance logistics.

A comparative analysis of the two samples showed that the average service life of air filters for Mazda vehicles is higher than that for Renault. Despite relatively close values of the coefficients of variation (0.44 and 0.41, respectively), Mazda filters exhibit greater dispersion of results, indicating a wider range of operating conditions. At the same time, the lower average service life of Renault filters, combined with a significant deterioration in their technical condition (reduced filtration efficiency), indicates a more intensive degradation process.

From the standpoint of reliability theory, this implies that the service life distribution function of filters has a pronounced probabilistic nature and requires description using cumulative distribution functions. The approximation results obtained in this study confirm the applicability of the normal distribution as a first approximation, which is consistent with approaches reported in the literature, where the use of the normal distribution for analyzing variations in technical parameters is justified.

At the same time, modern studies indicate the feasibility of applying more flexible models. In particular, study [7] demonstrates that dust accumulation in the filter element leads to a nonlinear

increase in the airflow resistance, directly affecting the fuel efficiency and engine power. This finding supports the observed signs of performance deterioration in both types of vehicles examined in this study.

In study [8], it is shown that air purification efficiency decreases during operation, and the optimal replacement interval depends on environmental conditions. The results obtained by the authors are consistent with the significant variability in the filter service life identified in this study (coefficient of variation exceeding 0.4).

Furthermore, publication [9] substantiates the transition from scheduled maintenance to approaches based on probabilistic models of component service life. This directly corresponds to the concept of filter replacement logistics proposed in this paper. In contrast to the studies cited [7-9], which are primarily based on laboratory or computational approaches, this work utilizes operational data, allowing for the inclusion of real-world vehicle operating conditions. This leads to greater variability in the results obtained, but simultaneously enhances their applied reliability.

A comparison of the results for Mazda and Renault allows the following generalizations: the service life of filters is a random variable with a wide range of values (6–17 thousand km); operating conditions have a decisive influence on the degradation rate of the filter material; the technical condition of the filter directly affects the energy and environmental performance of the engine; and the application of statistical models improves the accuracy of service life prediction [10].

From the perspective of techno-economic efficiency, the results of the study indicate the feasibility of implementing adaptive logistics for air filter replacement based on actual technical condition and statistical characteristics of service life [11]. Such an approach makes it possible to: reduce excessive costs associated with premature filter replacement; avoid operating vehicles with critically contaminated filters; improve fuel efficiency and engine durability; and optimize inventory management within maintenance systems.

Thus, the research results confirm that the integration of statistical analysis methods, reliability theory, and maintenance logistics is an effective tool for enhancing the operational efficiency of vehicles. The proposed approach to determining air filter replacement intervals can be applied as a component of an integrated vehicle reliability management system.

The practical significance of the obtained results lies in the possibility of using the established statistical characteristics of service life for adaptive maintenance planning. This allows for aligning filter replacement intervals with actual operating conditions and reducing operating costs without compromising the engine reliability.

Conclusions

1. As a result of the experimental studies, it was established that the service life of the engine air filters exhibits a pronounced stochastic nature and significantly depends on the vehicle operating conditions. For Mazda vehicles, the average mileage to filter replacement is 10.574 thousand km, while for Renault it is 9.561 thousand km, indicating differences in the degradation rate of the filter elements. The coefficient of variation of the filter service life was determined to be 0.44 for Mazda and 0.41 for Renault, confirming substantial heterogeneity of operating conditions and justifying the application of statistical methods for reliability assessment.
2. The study of the technical condition of filters revealed distinct stages of degradation (initial, intermediate, and limit), which are accompanied by reduced permeability and deterioration of the engine reliability performance. It is substantiated that traditional scheduled approaches to air filter replacement do not ensure an optimal level of reliability and techno-economic efficiency. The proposed approach, based on the use of statistical characteristics of the service life and condition monitoring, enables the implementation of adaptive filter replacement logistics.
3. A relevant direction for further research is the development of integrated models of techno-economic efficiency that take into account maintenance costs, changes in fuel consumption, engine service life, and environmental performance. Further advancement is also required in the development of logistics models for managing inventories of filter elements, which will allow optimization of supply processes and reduction of operating costs in transport enterprises.

4. The primary scientific and practical contribution of this work consists in establishing the statistical patterns of the air filter service life under real-world operating conditions and justifying an approach to adaptive replacement logistics based on reliability indicators.

Author contributions

Conceptualization, A. N., V. M.; methodology, A. N., V. M.; validation, A. N., V. M., Z. R., O. B. and Y. N.; formal analysis, A. N. and V. M.; data curation, Z. R., O. B., Y. N.; writing – original draft preparation, O. B. and Y. N.; writing – review and editing, Z. R. and O. B.; visualization, O. B.; project administration, A. N.; funding acquisition, A. N., V. M., Z. R., O. B. and Y. N. All authors have read and agreed to the published version of the manuscript.

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